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WADC TECHNICAL REPORT 52-322

CAUSES OF CRACKING IN HIGH-STRENGTH WELD METALS

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BATTELLE MEMORIAL INSTITUTE

FEBRUARY 1954

WRIGHT AIR DEVELOPMENT CENTER

WADC TECHNICAL REPORT 52-322
Part 2

CAUSES OF CRACKING IN HIGH-STRENGTH WELD METALS

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Battelle Memorial Institute

February 1954

Materials Laboratory
Contract No. AF 33(038)-12619
RDO No. 615-20 (A-B)

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by Battelle Memorial Institute, under USAF Contract No. AF 33(038)-12619. The contract was initiated under Research and Development Order No. 615-20 (A-B), "Welding, Brazing and Soldering of Metals", and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Major L. P. Marking acting as project engineer.

ABSTRACT

This report discusses an experimental investigation of the causes of cracking in high-strength weld metals. The research was conducted at Battelle during the third contract period, from August 12, 1952, to August 12, 1953. Specifically, the work included hot-ductility and weld-metal cracking tests on special high-strength steels and a metallographic examination of grain boundaries and inclusions in two of the steels. The results, although in an early stage, indicate that low-sulfur contents are associated with high hot ductility and high resistance to hot cracking. They also suggest a possible relationship between low-melting intergranular films and low hot ductility.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
for M. E. SORTE
Colonel, USAF
Chief, Materials Laboratory
Directorate of Research

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Causes of Cracking in High-Strength Weld Metals

The objective of this investigation is to obtain fundamental information on the causes of cracking in high-strength weld metals used to join high-strength alloy steels, and, on the basis of this knowledge, to devise methods for preventing such cracking. This report summarizes experimental work done during the third contract period from August 12, 1952, to August 12, 1953.

In the first contract period, a literature survey was made to supply background information on the cracking problem. This information is presented in the summary report, dated August 12, 1951. This survey indicates that hot cracking, the most prevalent form of cracking found in high-strength weld metals, is the result of low strength and low ductility in the temperature range from the liquidus down to about 1500 F. Therefore, in the second contract period, the groundwork was laid for correlating hot strength and hot ductility with hot-cracking susceptibility, and all three with composition. Apparatus was developed for measuring hot strength and hot ductility of weld metals as they cooled down from the molten state. In addition, four different weld-metal cracking tests were investigated. These developments are described in the summary report, dated August 12, 1952.

The present report discusses: (1) hot-tension tests on high-purity SAE 43XX-type steels and high-strength weld metals, and revisions made in the testing apparatus; (2) the development of a modified Lehigh restraint specimen, and tests on special heats of steel using this specimen; (3) metallographic studies of SAE 4340 steel used in hot-tension tests; (4) the preparation of new heats of steel for hot-tension and weld-metal cracking studies; and (5) the drawing of special welding wire.

SUMMARY

A limited number of hot-tension and weld-metal cracking tests were conducted on special high-strength steels during this report period. The hot-tension tests had to be discontinued midway through the report period when the induction-heating unit broke down. Also, considerable effort was spent on the development of a suitable cracking test for evaluating the special steels. For these reasons, the data presented in this report are in an early stage. It may be that the most valid conclusion that could be drawn from these data is the following: standard SAE 4340 steel has much lower ductility in the temperature range 2400 F to 1950 F, and it is much more susceptible to hot cracking than low-sulfur SAE 4340. These differences between the two steels are sizable and clear cut.

The work described in this report is summarized in the following sections.

Hot-Tension Studies

Hot-tension tests were conducted on one high-sulfur and five low-sulfur SAE 43XX steels, and on two steels simulating high-strength weld-metal compositions. The hot-tension tests were conducted in the temperature range 2700 F to 1800 F as the specimens cooled from the molten state. The test results indicated that increases in sulfur and carbon contents lowered hot strength and ductility, sulfur having the greater effect on ductility and carbon on strength. The scatter in the test results, however, together with the porosity in the test specimens, showed the need for modification of the testing apparatus. Changes were made so that porosity was greatly reduced. The data obtained so far are being checked, using the modified apparatus. The hot strength and ductility of additional experimental heats of steel simulating high-strength weld-metal composition are being determined.

Weld-Metal Cracking Tests

Considerable effort was spent on the development of a test specimen, hereafter referred to as the restrained weld specimen, which would exhibit various levels of restraint on a weld deposit. This specimen was patterned after the Lehigh restraint specimen. The experimental restrained weld specimen differs from the Lehigh specimen in two respects: (1) it consists of two parts welded together instead of being one integral plate; and (2) it uses a double-vee joint instead of a double-U joint. The changes are aimed at reducing the cost of the specimen and making it possible to run several tests on a small quantity of special steels. Welding-procedure tests were made with plain-carbon-steel base plate and commercial-steel wire, using the inert-gas consumable-electrode process. After procedures and techniques were established, the relative cracking susceptibilities of high- and low-sulfur SAE 4340 steels, which were deposited in base plate of the same composition, were determined at three levels of restraint. The low-sulfur deposit showed less hot cracking at the maximum restraint, which is the highest restraint level of the specimen, than the high sulfur showed at minimum restraint. This illustrated that the high-sulfur steel was much more crack susceptible than the low-sulfur steel. These data are in agreement with the hot-tension properties of these two steels. All the steel compositions for which hot-tension data are available will be tested using the restrained weld specimens in an attempt to correlate data from the two kinds of tests. Circular-groove and circular-patch tests will be conducted

also, as a check on the restrained weld tests and to determine if either of these tests is more satisfactory or simpler to use.

A heat of high-purity SAE 43XX composition was prepared to make additional base plate and wire for cracking tests. About 8-1/2 pounds of 3/32-inch high-purity SAE 43XX wire were drawn from 1/4-inch rod for the tests. The rod had been processed from the heats discussed in the summary report, dated August 12, 1952.

Metallographic Studies

The difference in fracture behavior between low- and high-sulfur hot-tension specimens suggested a possible dependence of fracture type on microstructure. Therefore, a metallographic study was made to determine the relationship between the nature and distribution of nonmetallic inclusions in the grain boundaries and the fracture behavior of the hot-ductility specimens.

A limited correlation was found between the hot ductility and the room-temperature microstructure of the melted zones of hot-tension specimens. This was demonstrated by the presence of films rich in FeS in the grain boundaries of the high-sulfur SAE 4340 specimens which exhibited brittle fracture above 1950 F. No films rich in FeS were found in the grain boundaries of the low-sulfur specimens. The change from ductile to brittle fracture in the low-sulfur specimens occurred between 2300 F and 2400 F. Light-etching networks were present in both the high- and low-sulfur SAE 4340 specimens. It appears that these networks contain MnS together with some of the metal-alloying elements (chromium, molybdenum, manganese, and nickel).

Weld deposits of low- and high-sulfur SAE 4340 were examined for evidence of sulfide segregation in the grain boundaries. Similar light-etching networks were found in both the weld deposits and hot-tension specimens. However, the nonmetallics were in the form of very small globules dispersed throughout the network of the weld deposits, as compared with globules and sulfide films in the grain boundaries of the hot-tension specimens.

The major part of the work in the next report period will be devoted to a continuation of the hot-tension and weld-metal cracking tests on special steel compositions. The objective will be to obtain further evidence that data from the two kinds of tests can be correlated. If this can be done, then two basic problems might be answered: (1) the temperature range in which cracking occurs; and (2) the nature and degree of impurities or alloy additions that cause cracking.

STUDY OF HIGH-TEMPERATURE DUCTILITY, CRACKING SUSCEPTIBILITY, AND METALLOGRAPHIC STRUCTURE OF SPECIAL SAE 43XX STEELS

During the previous contract period, apparatus was developed for rapid induction melting of the center section of a metal bar, then fracturing it in tension during the cooling cycle. This was devised to simulate a weld deposit subject to tension stresses from shrinkage and other factors as it cools down from the molten state. Provisions were made for measuring the temperature of the melted zone, the load required to fracture the bar, and the elongation of the test section.

No references were found in the literature on hot-tension tests of welds conducted during cooling from the melting temperature. Therefore, the studies in this investigation may have been the first to simulate welding conditions. The object was to find a relationship among composition, metallographic structure, hot-tension properties, and cracking susceptibilities of various weld metals.

The first series of hot-tension tests was run on commercial SAE 4340 and AISI C1111 steels. The data obtained from the two steels showed that strength and ductility increased with decreasing temperature in the range from 2600 F to 1800 F. The free-machining AISI C1111 steel was less ductile than the alloy steel. Its low ductility is thought to be due to its high sulfur content.

The original apparatus and the data on commercial SAE 4340 and AISI C1111 steels were discussed in the summary report, dated August 12, 1952.

Hot-tension tests were continued on special heats of SAE 43XX-type steel and on high-strength weld-metal compositions, in the contract period starting August 12, 1952. These are discussed below.

High-Temperature Tension Tests on High-Purity SAE 43XX Steels and High-Strength Weld Metals

Five high-purity SAE 43XX heats and one standard SAE 4340 heat were made for hot-tension studies. Their compositions are given in Table 1.

TABLE 1. COMPOSITION OF HIGH-PURITY AND STANDARD SAE 43XX STEELS

Heat Number	Chemical Composition, per cent							
	C	Mn	Si	Ni	Cr	Mo	S	P
1	0.33	0.76	0.26	1.91	0.83	0.25	0.005	0.008
2	0.45	0.64	0.33	1.88	0.82	0.26	0.008	0.005
3	0.59	0.66	0.29	1.93	0.81	0.26	0.006	0.007
4	0.46	0.66	0.20	1.94	0.83	0.26	0.037	0.026
5	0.46	0.77	0.25	1.89	0.90	0.24	0.008	0.004
6	0.46	0.69	0.21	1.83	0.82	0.21	0.006	0.004

Heats Nos. 1, 2, and 3 differ mainly in carbon content. These values vary from 0.33 to 0.59 per cent. Heats Nos. 2 and 4 have similar compositions, except for sulfur. Heats Nos. 5 and 6 are low-sulfur, extra-low-phosphorus SAE 4340 heats. Hot-ductility data were obtained for all six heats. (A seventh heat, which has to be tested, was also prepared. Its basic composition is similar to that of Heats Nos. 2, 5, and 6. In addition, it contains misch metal which may tie up the sulfur more effectively than would manganese.)

Hot-tension tests were made using the same apparatus described in the summary report, dated August 12, 1952. The specimens were melted by induction heating and, on the cooling cycle, were fractured at a preselected temperature in the range from 2700 F to 1800 F. Stress and strain were measured by a specially designed weigh bar and extensometer, respectively.

The experimental results are presented in Figures 1 through 4 for Heats Nos. 1 through 4. The hot-ductility values for Heats Nos. 1, 2, and 3 are compared in Figure 1, while the hot strengths for the same heats are compared in Figure 2. These comparisons show the effects of carbon on hot strength and ductility. Similar comparisons for Heats Nos. 2 and 4, in Figures 3 and 4, show the effects of sulfur on hot-tension properties.

The data from tests on Heats Nos. 5 and 6 showed unusual scatter, indicating the need for an improvement of the testing apparatus. The changes made in the apparatus are described in Appendix I. Tests on Heats Nos. 5 and 6 are being repeated.

Two commercial high-strength weld-metal compositions also were studied before the apparatus was modified. The compositions are shown on page 8.

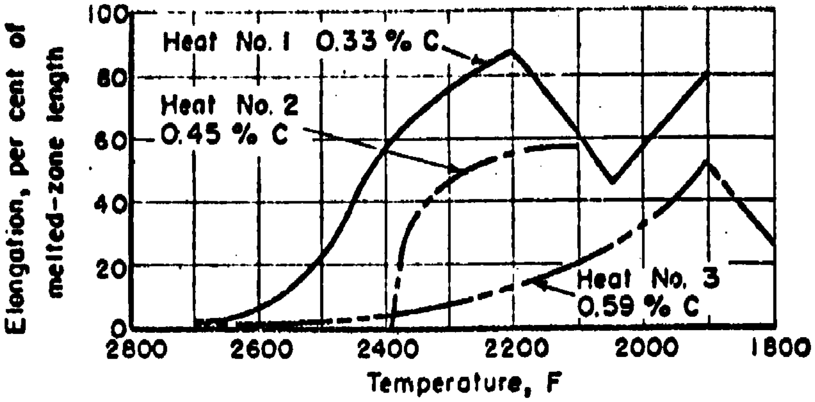


FIGURE 1. COMPARISON OF HOT DUCTILITY OF SAE 43XX HEATS NOS. 1, 2, AND 3

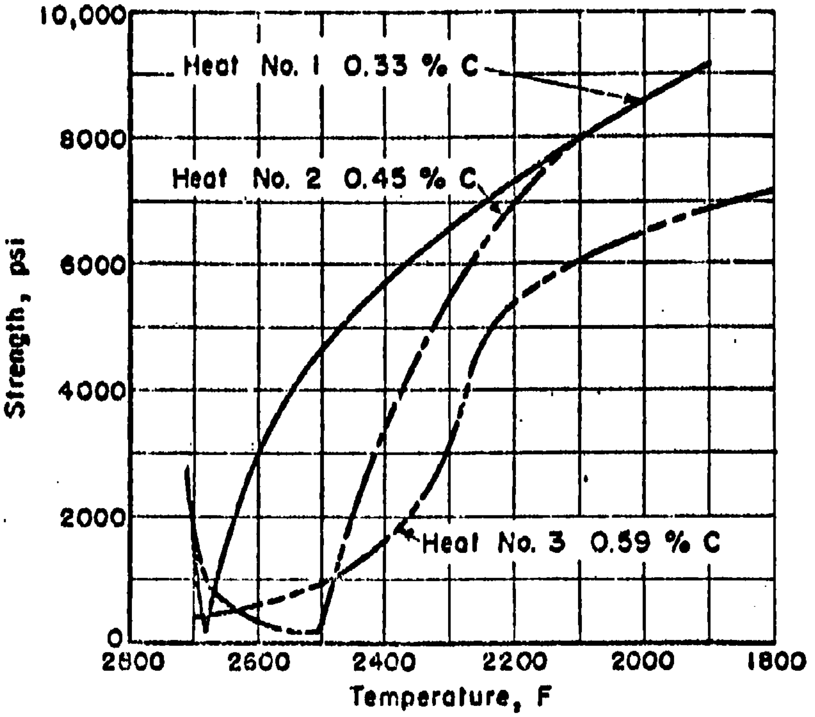


FIGURE 2. COMPARISON OF HOT STRENGTH OF SAE 43XX HEATS NOS. 1, 2, AND 3

A-4669

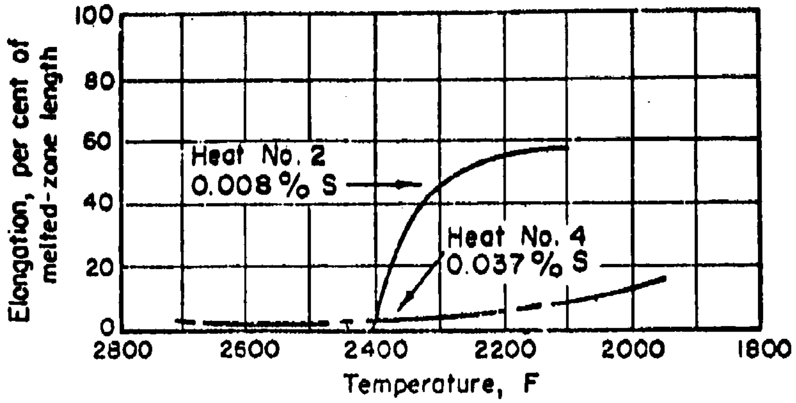


FIGURE 3. COMPARISON OF HOT DUCTILITY OF SAE 43XX HEATS NOS. 2 AND 4

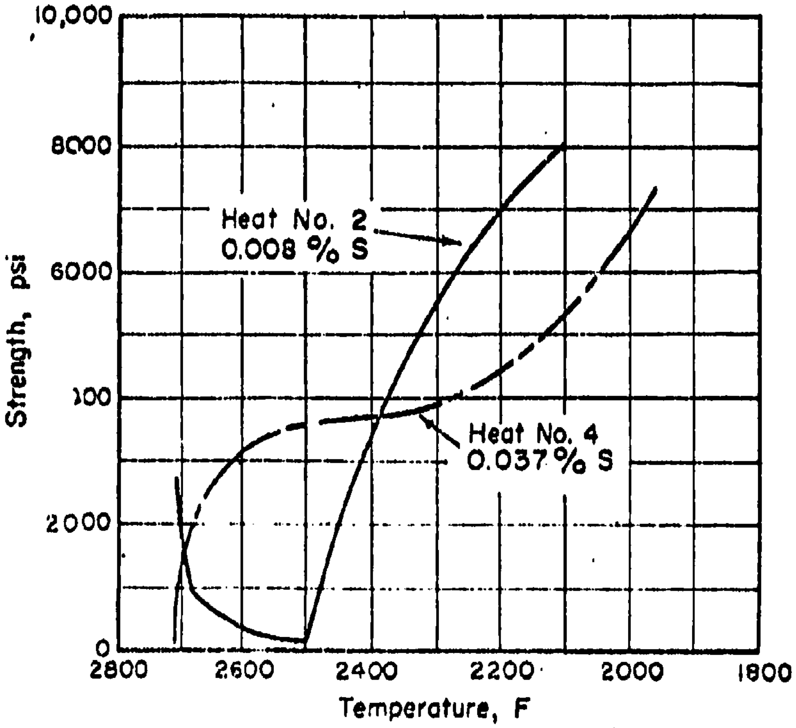


FIGURE 4. COMPARISON OF HOT STRENGTH OF SAE 43XX HEATS NOS. 2 AND 4

A-4670

Electrode	Chemical Composition, per cent C	Mn	Si	Cr	Ni	Mo	V	S	P
C	0.14	0.75	0.48	0.95	1.75	0.80	0.18	0.021	--
D	0.12	1.00	0.50	1.20	1.30	0.60	0.13	0.015	--

The electrodes have the same designations used in the summary report of August 12, 1952.

The weld-metal specimens were machined from deposits in a single-vee joint in 1-inch-thick SAE 4340 steel. Machining was done transverse to the direction of welding so that only weld metal would be melted in the hot-tension tests. The data obtained are plotted and compared in Figures 5 and 6.

The results from the hot-tension tests conducted thus far in the program showed some scatter, and several points will be checked before they are considered reliable. However, results obtained from the various steels indicate general trends which are believed to be correct. Possible sources of error that were inherent in the original apparatus are discussed in Appendix I.

From an examination of Figures 1 through 4, it appears that increases in carbon and sulfur contents result in lower hot strength and ductility. It appears also that sulfur has more influence than carbon on hot ductility and less on hot strength. The first observation is supported by the curves in Figures 5 and 6. Weld Metal D (0.12% carbon, 0.015% sulfur) is stronger and more ductile than Weld Metal C (0.14% carbon, 0.021% sulfur) in the 2400 F to 1800 F temperature range.

The detrimental effect of sulfur on the hot ductility of tensile specimens was demonstrated further by examination of the fractured tensile specimens. The specimens from Heat No. 2 (0.008% sulfur) showed a sharp change from brittle to ductile fracture between 2400 F and 2300 F, while those from Heat No. 4 (0.037% sulfur) showed brittle fractures all the way down to 1950 F. As a result of this difference in behavior between low-sulfur and high-sulfur SAE 4340 heats, metallographic studies (discussed later) were carried out in an attempt to correlate brittle- and ductile-fracture types with microstructure.

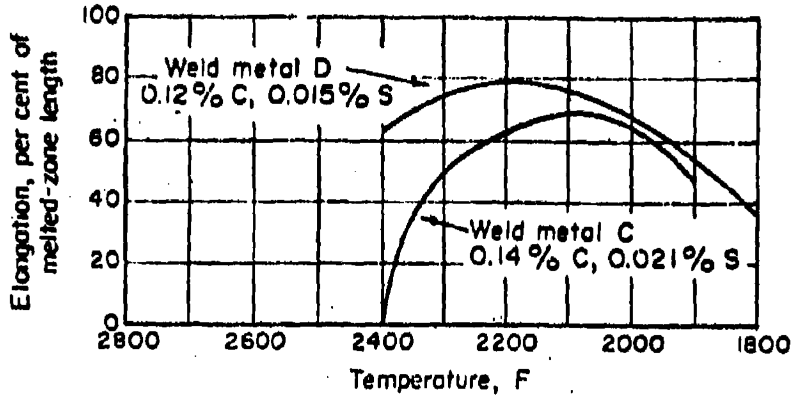


FIGURE 5. COMPARISON OF HOT DUCTILITY OF WELD METALS C AND D

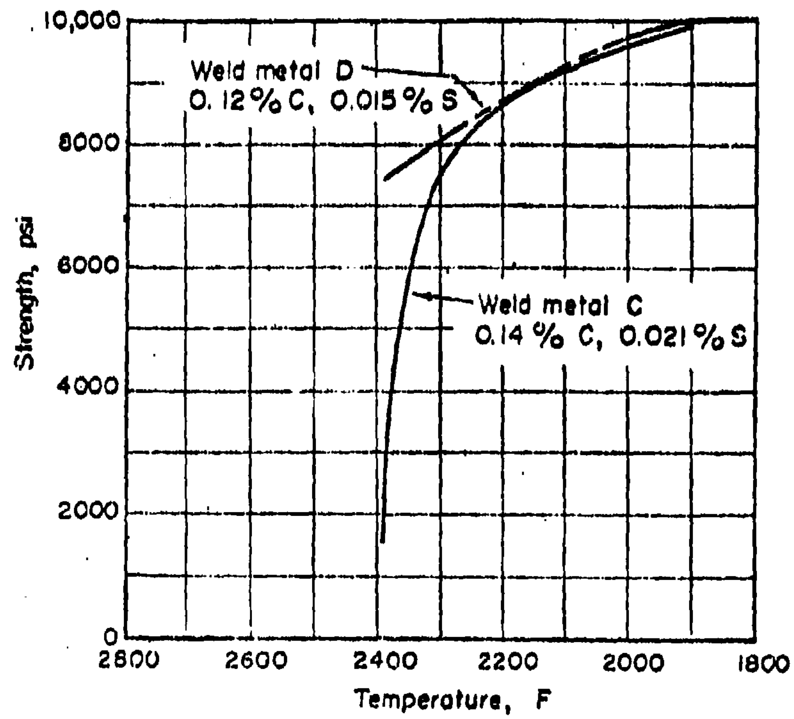


FIGURE 6. COMPARISON OF HOT STRENGTH OF WELD METALS C AND D

A-4672

Weld-Metal Cracking Tests on Low- and High-Sulfur SAE 4340 Steel

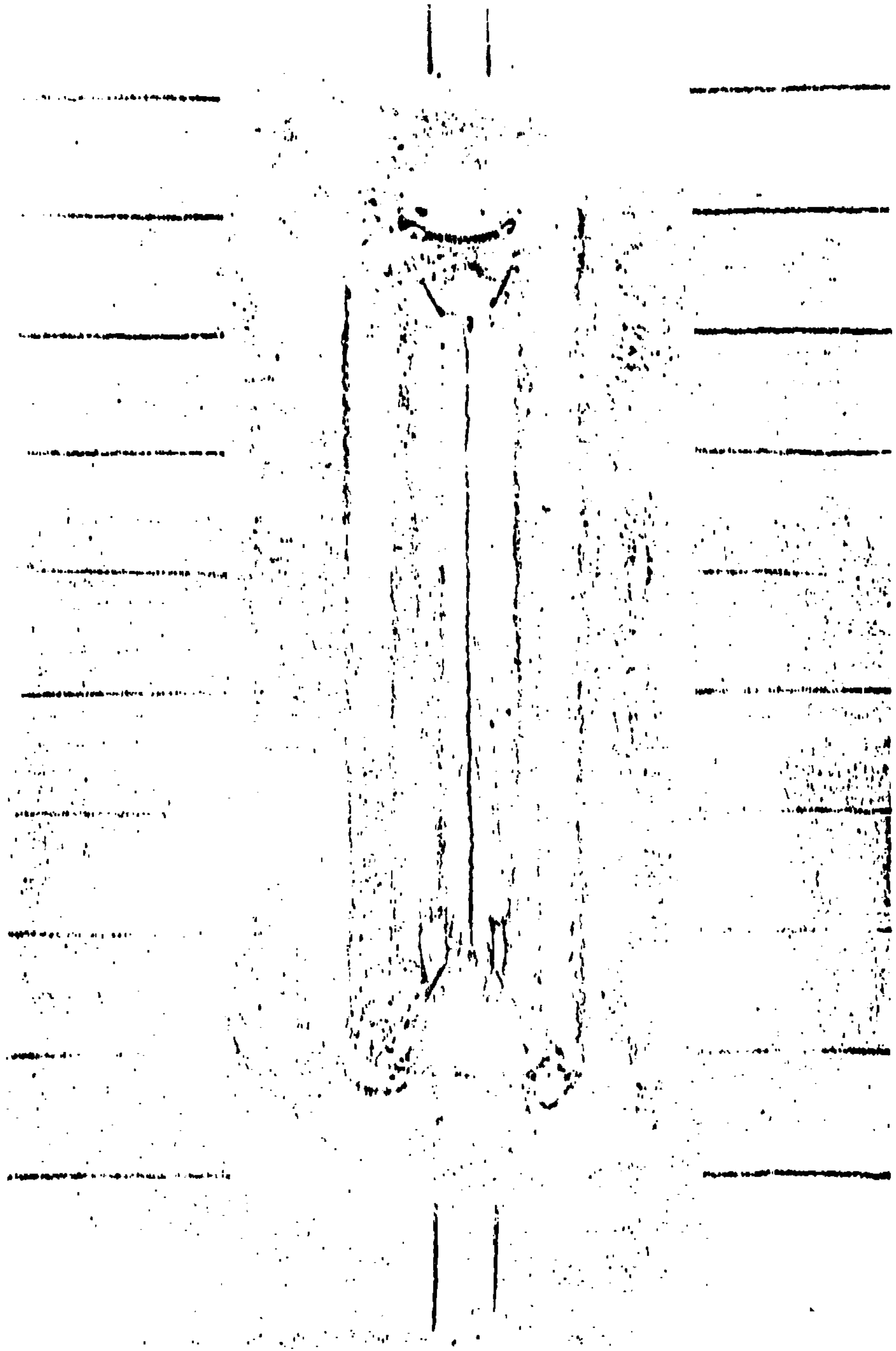
In order to run tests on cracking susceptibility, it was necessary to reduce experimental heats (six high-purity and one standard) of SAE 43XX steel to wire. Since the wire diameter was to be 3/32 inch, the 1/4-inch wire rolled originally had to undergo a 62.5 per cent reduction. Wire of SAE 43XX composition work hardens rapidly. Therefore, each heat had to be annealed three or four time. [illegible] he drawing procedure. Elaborate precautions were taken to prevent pickup of oxygen and other elements that might contaminate the high-purity steels. This was accomplished by sealing the wire in a retort in which the pressures were reduced to as low as several tenths of a micron.

Cracking susceptibility tests were run on low- (Heat No. 2) and high-sulfur (Heat No. 4) SAE 4340 steels using a modified Lehigh restraint specimen and the inert-gas consumable-electrode process. (See Appendix II for development and nature of modified specimen and welding procedure.)

In the first test, high-sulfur (0.037% sulfur) SAE 4340 wire was deposited in base metal of the same composition. In the second test, low-sulfur (0.008% sulfur) SAE 4340 wire was deposited in low-sulfur SAE 4340 base metal. Both welds were made at a restraint level of 4 inches, that is, X' in Figure 24 (Appendix II) was 2 inches.

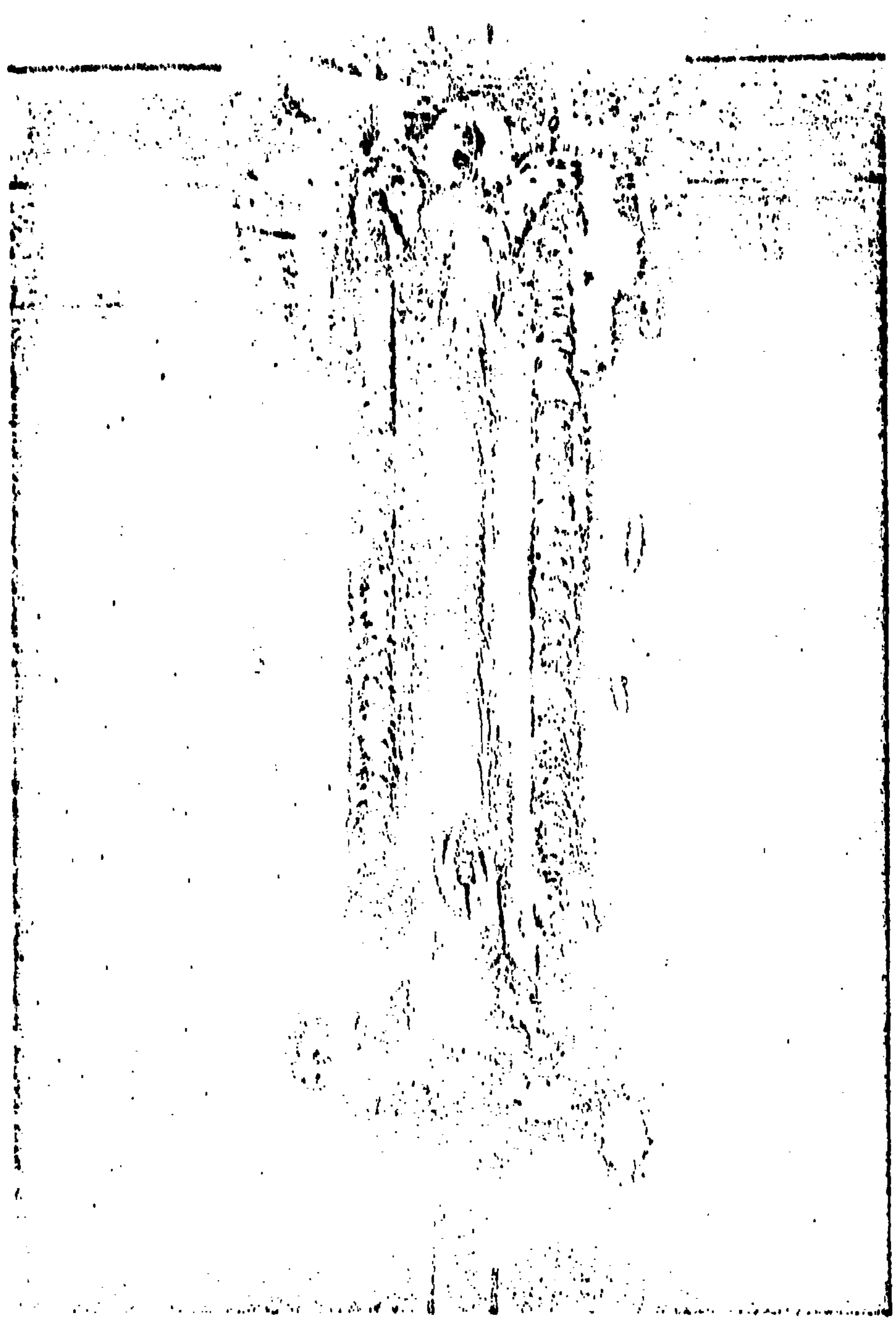
The specimen welded with high-sulfur wire is shown in Figure 7, and the one welded with low-sulfur wire is shown in Figure 8. The crack in the high-sulfur deposit extends the length of the weld, while only a crater crack is visible in the low-sulfur weld. After removal from their frames, both inserts were fractured in a bending press. The halves of the high-sulfur insert are shown in Figure 9. The presence of a blue oxide coating (darkest temper color in Figure 9) on the fracture face of the high-sulfur deposit indicated a hot crack. There is no such discoloration of the low-sulfur fracture, also shown in Figure 9. The dark streak in the fracture face is the result of a ridge between the base metal and weld metal. Check tests at the 4-inch restraint level confirmed these results.

The next restraint levels tried were 2 inches and 8 inches of the restrained weld specimen. The high-sulfur composition was tested at the 2-inch level, and the low-sulfur composition at the 8-inch level. The high-sulfur weld metal cracked about one-half the length of the weld at this low level of restraint. The low-sulfur weld developed a hot crack about 1/2 inch long when tested at the high level of restraint. Check tests are in progress. So far, the results are in accord with hot-ductility data obtained on these steels.



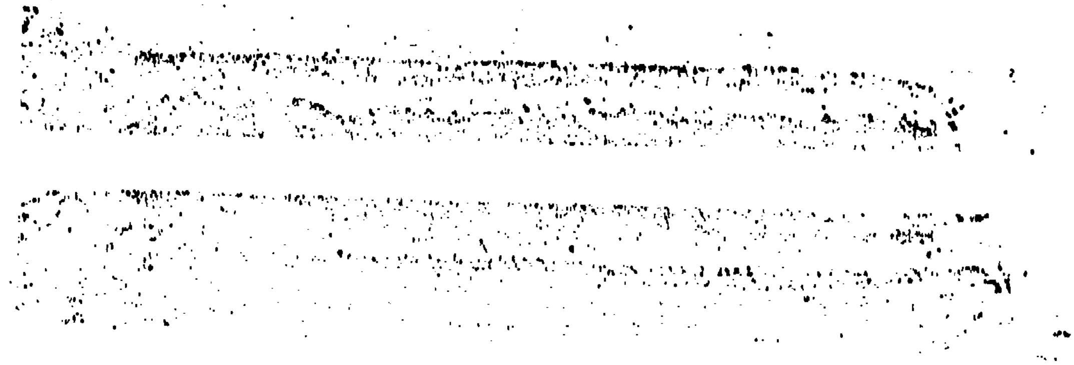
N5639

FIGURE 7. MODIFIED LEHIGH RESTRAINT SPECIMEN WELDED WITH HIGH-SULFUR (0.037% S) SAE 4340 FILLER WIRE AND BASE-METAL INSERT



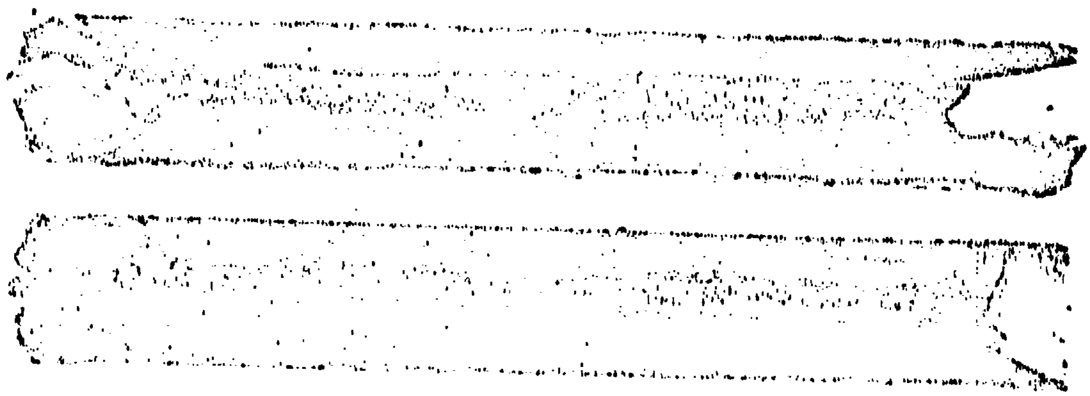
N5822

FIGURE 8. MODIFIED LEHIGH RESTRAINT SPECIMEN WELDED WITH LOW-SULFUR (0.008% S) SAE 4340 FILLER WIRE AND BASE-METAL INSERT



N5638

High-Sulfur SAE 4340



N5941

Low-Sulfur SAE 4340

FIGURE 9. FRACTURED HIGH-SULFUR (ABOVE) AND LOW-SULFUR (BELOW) SAE 4340 INSERTS SHOWN IN FIGURES 7 AND 8

The low amount of hot cracking obtained with the low-sulfur weld deposits is very encouraging. It appears that controlling sulfur may be one important means of controlling hot cracking.

Some of the low-sulfur test specimens cold cracked at temperatures between 800 F and room temperature. It is believed that this type of cracking can be controlled by proper preheating and postheating of the weldments. Further work along these lines is in progress.

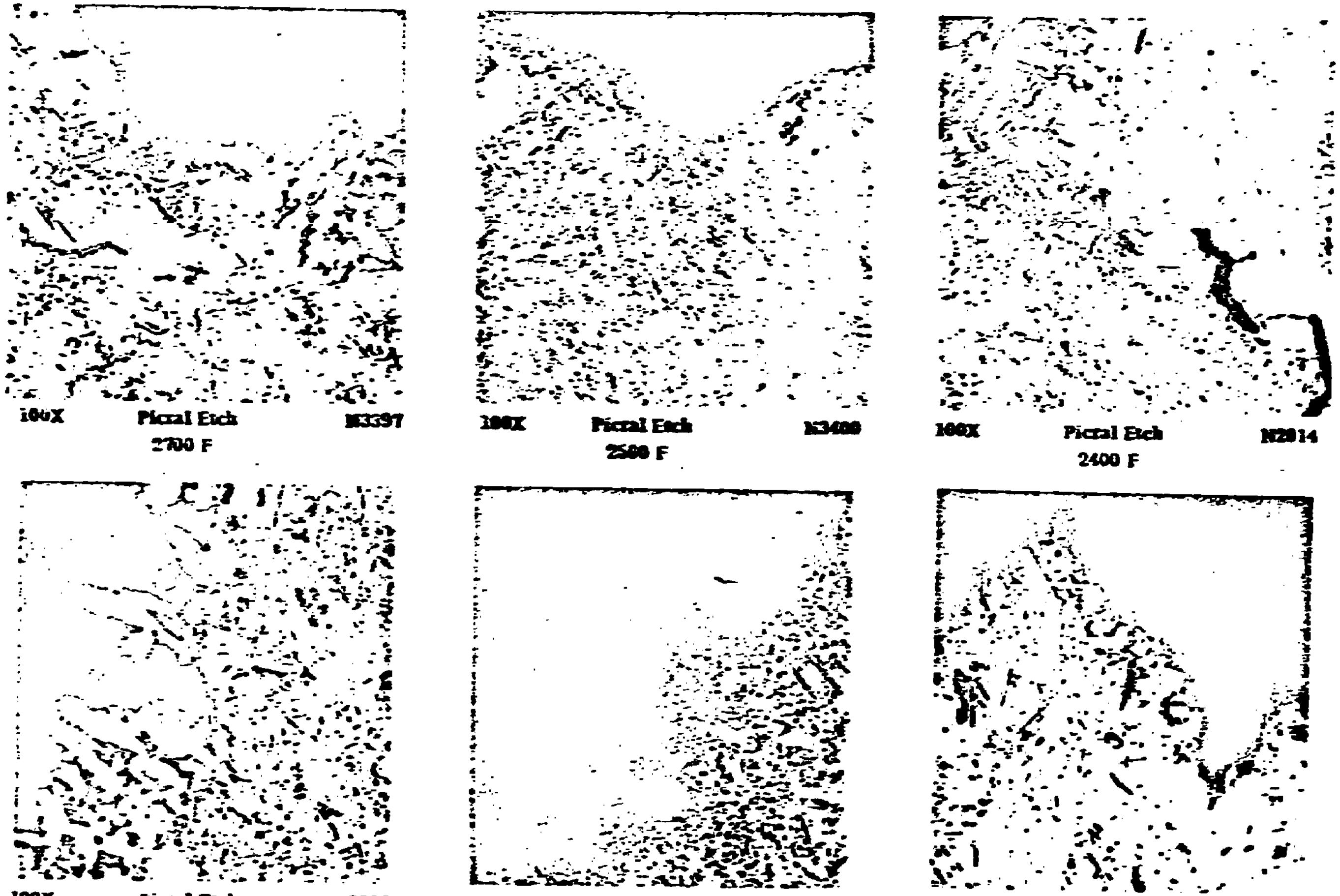
Metallographic Studies of Low- and High-Sulfur SAE 4340 Steel

As mentioned in a previous section, the fractures of the low-sulfur tension specimens changed abruptly from brittle to ductile behavior in the temperature range 2400 F to 2300 F, while the fractures of the high-sulfur specimens remained brittle down to 1950 F. A metallographic study was started as a result of these findings. The study attempted to correlate the hot ductility of low- and high-sulfur SAE 4340 with the segregation of nonmetallics in the grain boundaries of the melted zones of tested hot-tension specimens.

Microstructures of Fractured Hot-Tension Specimens

The first phase of the metallographic study represented an attempt to correlate the hot ductility and microstructures of tested hot-tension specimens. Longitudinal sections were taken through the melted zones of fractured low- and high-sulfur hot-tension specimens. The polished-and-etched structures are shown at 100X in Figures 10 and 11. A representative structure of the steel shown in Figure 11 appears in Figure 12 at 500X. The change from brittle to ductile behavior, as the test temperature was lowered, is manifested in Figure 10 by the change from equiaxed to elongated grains. The structures themselves are martensitic (or bainitic) in nature. Through them run light-etching networks, upon which attention was focused.

Two techniques were used to prove that the light-etching networks are not a separate phase but merely of such a nature that they etch more slowly than the surrounding structure. The first technique involved overetching, and the second involved repolishing and re-etching with extremely dilute picral. Overetching brought out the usual martensitic structure in the light areas. The extremely dilute picral, which attacks the metal slowly and uniformly, showed a single martensitic structure. The light-etching networks were thought to be rich in segregates, and, for this reason, etched slower.



100X Picral Etch N3397
2700 F

100X Picral Etch N3400
2500 F

100X Picral Etch N2814
2400 F

100X Picral Etch N2812
2300 F

100X Picral Etch N5643
2200 F

100X Picral Etch N3399
2100 F

FIGURE 10. MICROSTRUCTURES OF LOW-SULFUR SAE 4340 (HEAT NO. 2, 0.008% S) HOT-TENSION SPECIMENS FRACTURED AT TEMPERATURES INDICATED

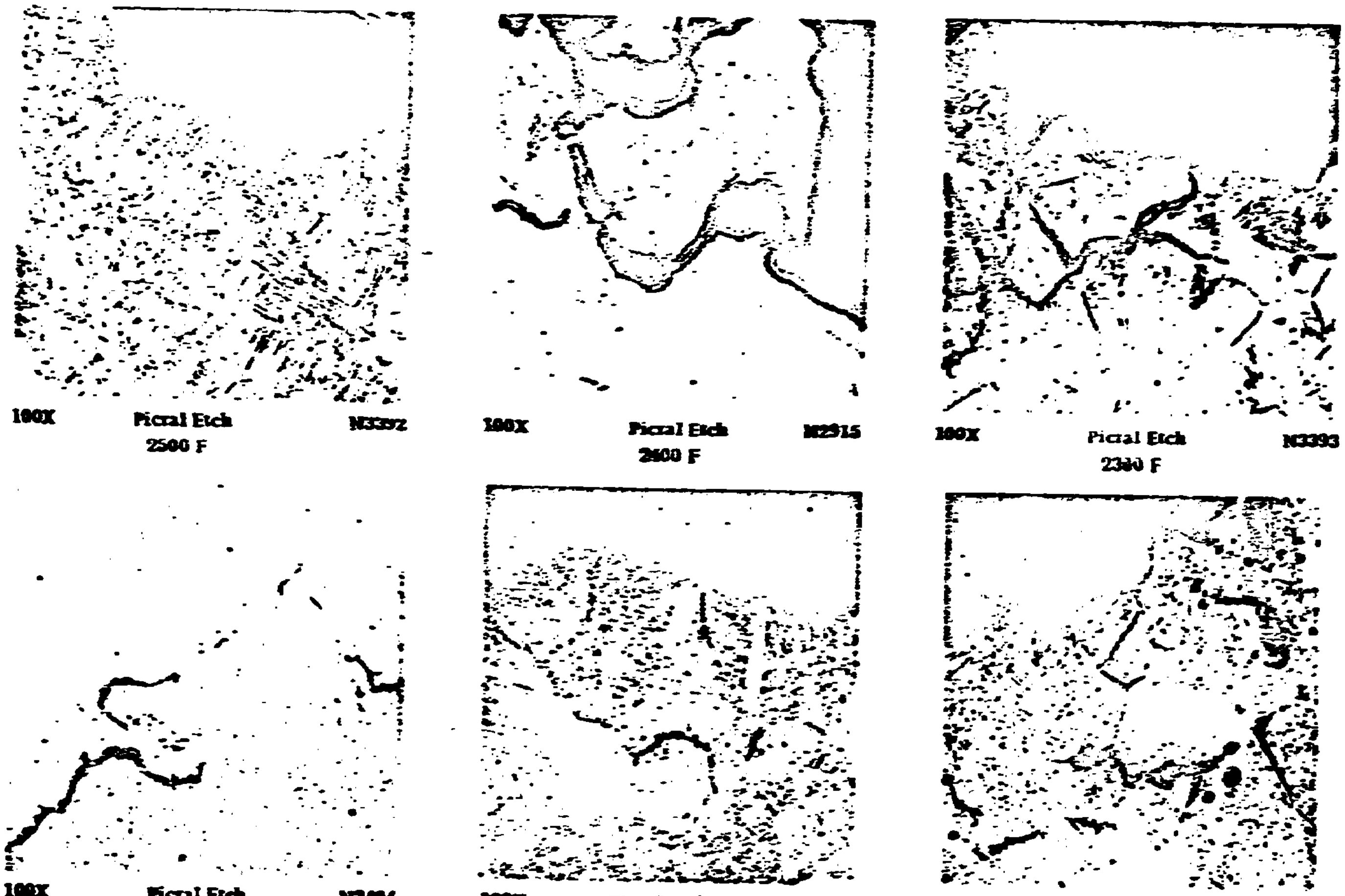
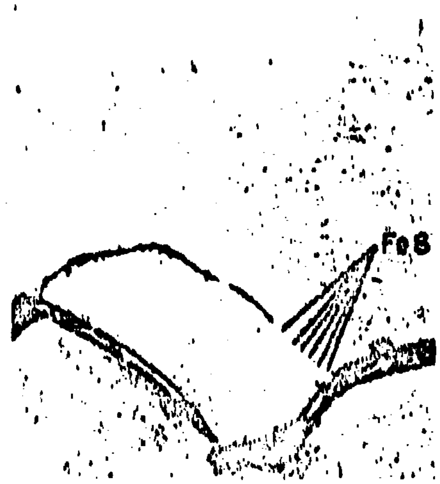


FIGURE 11. MICROSTRUCTURES OF HIGH-SULFUR SAE 4340 (HEAT NO. 4, 0.037% S) HOT-TENSION SPECIMENS FRACTURED AT TEMPERATURES INDICATED



500X Picral Etch N3102

FIGURE 12. MICROSTRUCTURE OF HIGH-SULFUR SAE 4340 (HEAT NO. 4, 0.037% S) HOT-TENSION SPECIMEN FRACTURED AT 2100 F

Figure 12 shows that sulfides segregated into the light-etching areas. Inclusions rich in iron sulfide were identified by their anisotropic behavior under plane-polarized light in all the high-sulfur SAE 4340 specimens examined. None was found in the low-sulfur SAE 4340 specimens. The photomicrograph at 500X in Figure 12 illustrates the tendency of the sulfide to appear as an extremely thin film in the light-etching areas. (In this case, it is broken up by globular sulfides.) It is pale yellow in color, but takes on a brownish tinge when exposed to air. At 500X, it does not have a sharp outline. The photomicrograph in Figure 12 also illustrates the tendency of fissures to be present in the vicinity of these sulfides.

Nonferrous sulfides segregated into the light-etching areas of both low- and high-sulfur steels. Manganese sulfide (MnS) probably predominates, with solid solutions of iron sulfide in manganese sulfide and other combinations also possible. Pure manganese sulfide is light gray and has a distinct outline. The nonferrous sulfides occur in globular as well as in stringer form.

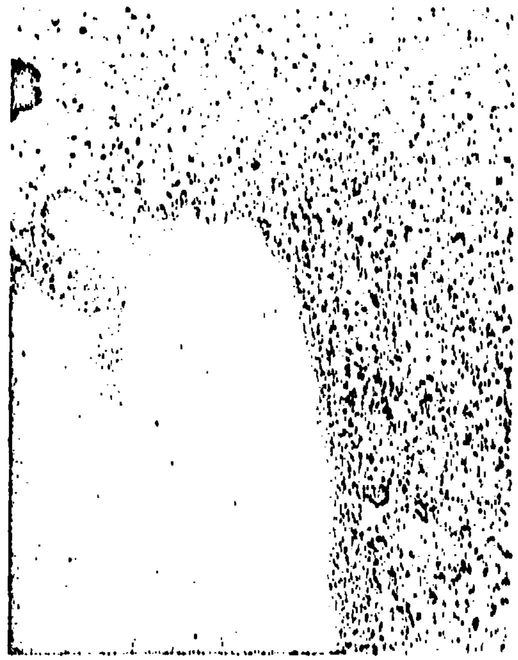
Figure 12 does not confirm or deny the existence of nonsulfide segregates. Two experiments were tried to determine if the light-etching areas might contain extra carbon, or one or more of the metallic elements such as nickel, chromium, molybdenum, and manganese.

The object of the first experiment was to determine if carbon segregation caused the light-etching areas. The mating half of the low-sulfur specimen shown in Figure 10 (testing temperature 2300 F) was placed in the furnace at 1600 F, and held for 2 minutes. This was sufficient time for segregated carbon but not the metallic elements to diffuse. The last step in the procedure was a water quench.

It cannot be concluded from the photomicrograph in Figure 13 that the carbon had segregated. The light-etching network is too well preserved to draw even a qualitative conclusion. Therefore, it was concluded that concentrations of other elements were present in the light-etching areas.

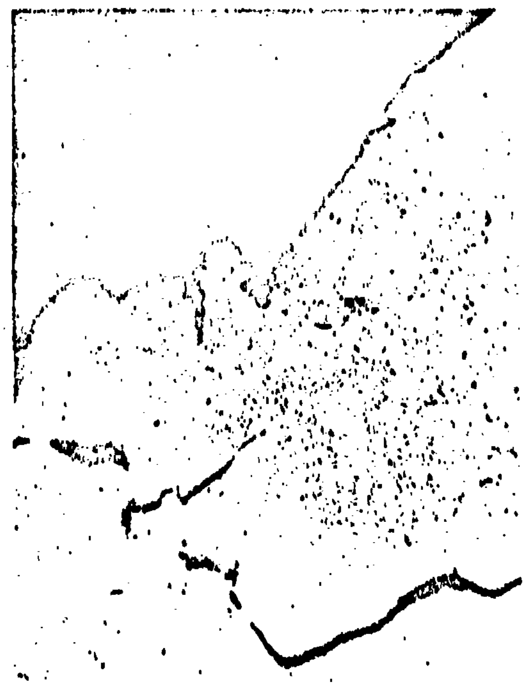
In the second experiment, the mating half of the high-sulfur specimen shown in Figure 11 (testing temperature 2200 F) was brought up to 1600 F in a cold furnace, and held at that temperature for 20 minutes. The total heating time at temperatures above 1375 F (Ac_3 temperature for SAE 4340) was about 55 minutes. This should have been sufficient time for segregated carbon to go into solution. The specimens were water quenched from 1600 F.

The same general network seen in Figure 11 (testing temperature 2200 F) persists in the heat-treated mate shown in Figure 14. Some diffusion must have occurred, since it is not completely preserved. The carbon was certainly diffused by this treatment; therefore, the light-etching areas must contain a concentration of one or more of the other alloying elements.



100X Picral Etch N5227

FIGURE 13. PHOTOMICROGRAPH SHOWING PRESERVATION OF LIGHT-ETCHING NETWORK IN TESTED LOW-SULFUR SAE 4340 HOT-TENSION SPECIMEN AFTER SHORT-TIME AUSTENITIZING



100X Picral Etch N5430

FIGURE 14. PHOTOMICROGRAPH SHOWING PARTIAL PRESERVATION OF LIGHT-ETCHING NETWORK IN TESTED HIGH-SULFUR SAE 4340 HOT-TENSION SPECIMEN AFTER PROLONGED AUSTENITIZING

Microstructures of Weld Deposits

A metallographic study was made of high- and low-sulfur SAE 4340 weld deposits to determine the nature and distribution of nonmetallic inclusions. The filler wires were deposited in restrained weld-test specimens using the inert-gas consumable-electrode welding process. Transverse sections were taken through hot-cracked portions of the welds for examination. Nickel was electrodeposited on the fracture surfaces to prevent oxidation and damage of the specimen.

Two photomicrographs of the high-sulfur specimen are shown, one in Figure 15 at 100X, and the other in Figure 16 at 500X. The inclusions occur as small highly dispersed globules (Figure 15). The lighter ones are probably sulfides; the dark ones may be silicates (Figure 16). Duplexed inclusions also are evident. The network seen in Figure 15 is actually light etching, but was photographed in relief so that the inclusions could be shown more clearly. It is the same type of network that was observed in Figures 10 and 11. Therefore, it is possible that similar segregation has taken place in the weld deposit and hot-tension specimens. The low-sulfur specimen appeared to differ from the high-sulfur specimen only to the extent of having fewer sulfide inclusions. The study of weld deposits will be continued in an attempt to draw further comparisons between the microstructures of tested hot-tension specimens and weld deposits.

Discussion of Results

Tests on low- and high-sulfur SAE 4340 steels have shown that hot-tension and cracking-susceptibility data may be correlated. Furthermore, metallographic studies of the same steels indicated a possible dependence of hot ductility on grain-boundary conditions.

The ability of sulfur to lower hot ductility was demonstrated in Figure 3, and its role as a promoter of hot cracking was shown in a comparison of Figures 7 and 8. Therefore, there is reason to believe that a direct relationship exists between hot cracking and low hot ductility, and between hot cracking and high sulfur content. The photomicrograph in Figure 12 shows a low-melting film (FeS) which may be responsible for low hot ductility and, consequently, hot cracking.

It is well known that low-melting compounds like iron sulfide (melting point 2183 F) segregate in network patterns. The alloying elements may form low-melting constituents which segregate also, so that the true solidus temperature for an SAE 4340 steel weld deposit might conceivably be lowered by several hundred degrees. It is believed that segregation of low-melting constituents would promote hot cracking in weld deposits.

100X Picral Etch N8266

FIGURE 15. HIGH-SULFUR SAE 4340 WELD DEPOSIT SHOWING INCLUSIONS AND NETWORK

500X Picral Etch N8267

FIGURE 16. HIGH-SULFUR SAE 4340 WELD DEPOSIT SHOWING NATURE OF INCLUSIONS

Most often, cracks were found in areas of high iron sulfide concentration. The possibility that the cracks initiate and propagate along liquid films of iron sulfide is strongly suggested. Figure 12 shows cracks in the vicinity of iron sulfide. The cracks contain debris from the polishing operation.

Iron sulfide was found in the high-sulfur SAE 4340 specimens, but not in the low-sulfur specimens. If it were found in segregated patches in the low-sulfur specimens with little hot ductility, a relationship might have been postulated between critical concentrations of iron sulfide and brittle fracture. Such a relationship should not be ruled out, however, until higher magnifications than 500X have been used. The possibility remains that other low-melting constituents are related to brittle fracture.

It was expected that most of the sulfur in the two heats studied would be tied up as MnS rather than FeS. The manganese-to-sulfur ratios in the low- and high-sulfur heats were 80/1 (0.64/0.008) and 18/1 (0.66/0.037), respectively, compared with a ratio of about 5/1 in commercial steels.

If further tests confirm the findings that hot-tension and cracking-susceptibility data can be correlated, then the following problems would be nearer solution: (1) the temperature range in which cracking occurs; and (2) the nature and degree of impurities or alloy additions which cause cracking.

FUTURE WORK

Future work will follow the pattern of work to date. Further hot-tension testing and weld-cracking testing will be done on special compositions of weld metal.

Hot-Tension Tests

Hot-tension tests are being made with the modified hot-tension apparatus to check the data presented in this report. In order to conserve material for these check tests, 2-inch lengths were cut from the undrilled ends of the hot-tension specimens already tested. These pieces were flash welded to 2-1/2-inch by 1/2-inch lengths of SAE 4130 steel at both ends to make new hot-tension specimens. Other hot-tension tests will be made on specimens from Heat No. 7, which is the low-sulfur SAE 4340 heat containing misch metal. Misch metal may be very effective in tying up sulfur.

In addition, two 200-pound induction heats of steel were made to study the effects of sulfur, and sulfur plus misch metal, on the hot-tension and hot-cracking properties of a weld-metal composition. The compositions of the heats are similar to that of weld metal deposited with an E12016 type electrode (Weld Metal C), as shown in Table 2. The chief differences are the sulfur content and the presence of misch metal and aluminum in the experimental heats, as shown in Table 2.

TABLE 2. COMPOSITION OF EXPERIMENTAL HEATS FOR HOT-TENSION SPECIMENS AND FILLER WIRE

Heat Number	Chemical Composition, per cent								
	C	Mn	Si	Ni	Cr	Mo	V	S	Al(1)
8-A	0.14	0.88	0.55	1.77	1.00	1.00	0.19	0.007	0.066
8-B	As above, plus three pounds per ton of misch metal								
9-A	0.15	0.78	0.51	1.73	0.93	1.03	0.19	0.031	0.085
9-B	As above, plus three pounds per ton of misch metal								
Commercial Weld Metal C(2) (E12016)	0.14	0.75	0.48	1.75	0.95	0.80	0.18	0.021	--

(1) Analyzed spectrographically. Other elements determined chemically.
(2) Manufacturer's analysis except for sulfur.

The basic material for the low-sulfur (0.007% sulfur) heat was electrolytic iron containing 0.005 per cent sulfur. A MgO crucible and argon-gas blanket were used in the preparation of both heats.

One-half of each heat was forged and rolled into 11/16-inch and 1/4-inch rounds for machining hot-tension specimens and drawing welding wire, respectively.

Weld-Metal Cracking Tests

Restrained weld tests are in progress with low- and high-sulfur SAE 4340 weld deposits to determine the highest degree of restraint without cracking. After the effect of sulfur on cracking susceptibility has been studied, the same type of test will be used to study the other compositions

investigated in hot-tension tests. Attempts will be made also to eliminate cold cracking which occurs occasionally in the Lehigh tests. This might be reduced by using a small amount of preheat.

Further tests are being planned with circular-groove and circular-patch specimens. The data obtained from them should serve as a check on the Lehigh test data.

Data for this report are recorded in Laboratory Notebooks No. 5485, pp 94-100, No. 7893, pp 1-100, and No. 8318, pp 1-45.

AJJ:PJR:CBV/NCL:bep

APPENDIX I

APPENDIX I

Modification of Hot-Tension Testing Apparatus

During the course of testing over 100 hot-tension specimens, considerable difficulty was encountered with porosity and shrinkage cavities in the melted area of the test bars. Various minor adjustments in the apparatus improved the condition but did not reduce it effectively. Repeat tests were often required to obtain reliable data. An unusual amount of trouble was encountered while testing high-purity Heats Nos. 5 and 6.

It was decided, at this point, to completely modify the apparatus to eliminate the operating problem. The major features of the original apparatus that needed improvement were:

1. The quartz sleeves for retaining the melt. These sleeves were not uniform in ID. In the as-received condition, the ID varied by 15 per cent. A method of obtaining uniform dimensions was needed so that the melted section of the test bar would be uniform.

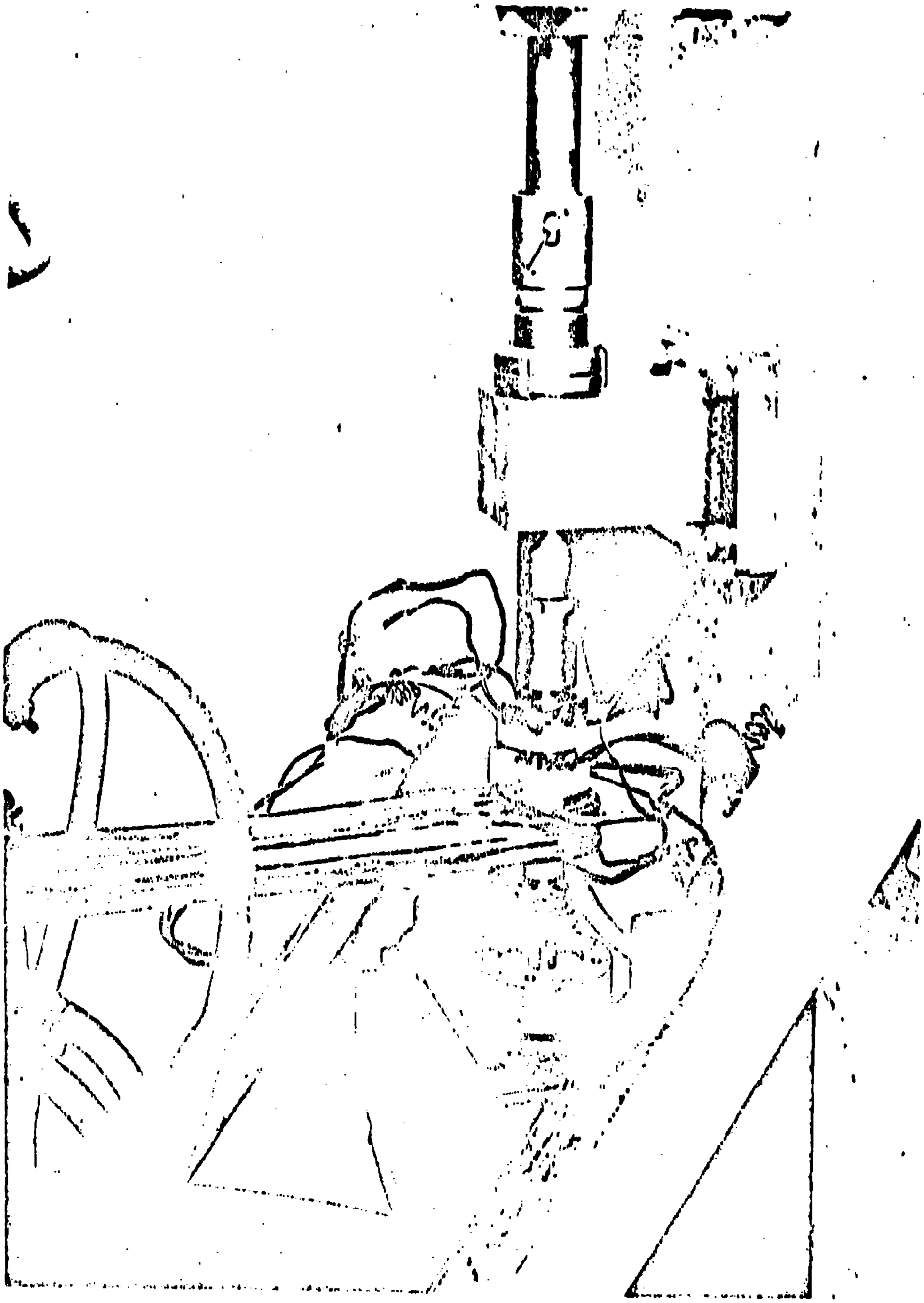
2. Alignment of upper and lower halves of specimen during melting. The apparatus did not prevent the two halves of the specimen from going slightly out of alignment during melting. This increased the problems with quartz sleeves and shrinkage cavities.

3. Provisions to allow shrinkage while melted specimen cooled. There was evidence in some tests that restraint to normal shrinkage occurred during cooling to test temperature. Better provisions to allow free shrinkage were needed.

4. Temperature-measuring system. In some cases, temperature measurements were questionable. was believed that more direct and reliable measurements might be made.

Changes in the apparatus were made to overcome the deficiencies. They are shown in Figures 17, 18, and 19.

The first change was made in the quartz sleeves used to contain molten metal. As received from the manufacturer, the tubing from which the sleeves are made has a 7.5 per cent tolerance in the nominal 1/2-inch ID. Thereafter, many of the sleeves were considerably oversize. When



N1378

FIGURE 17. IMPROVED HOT-TENSION-TEST ASSEMBLY

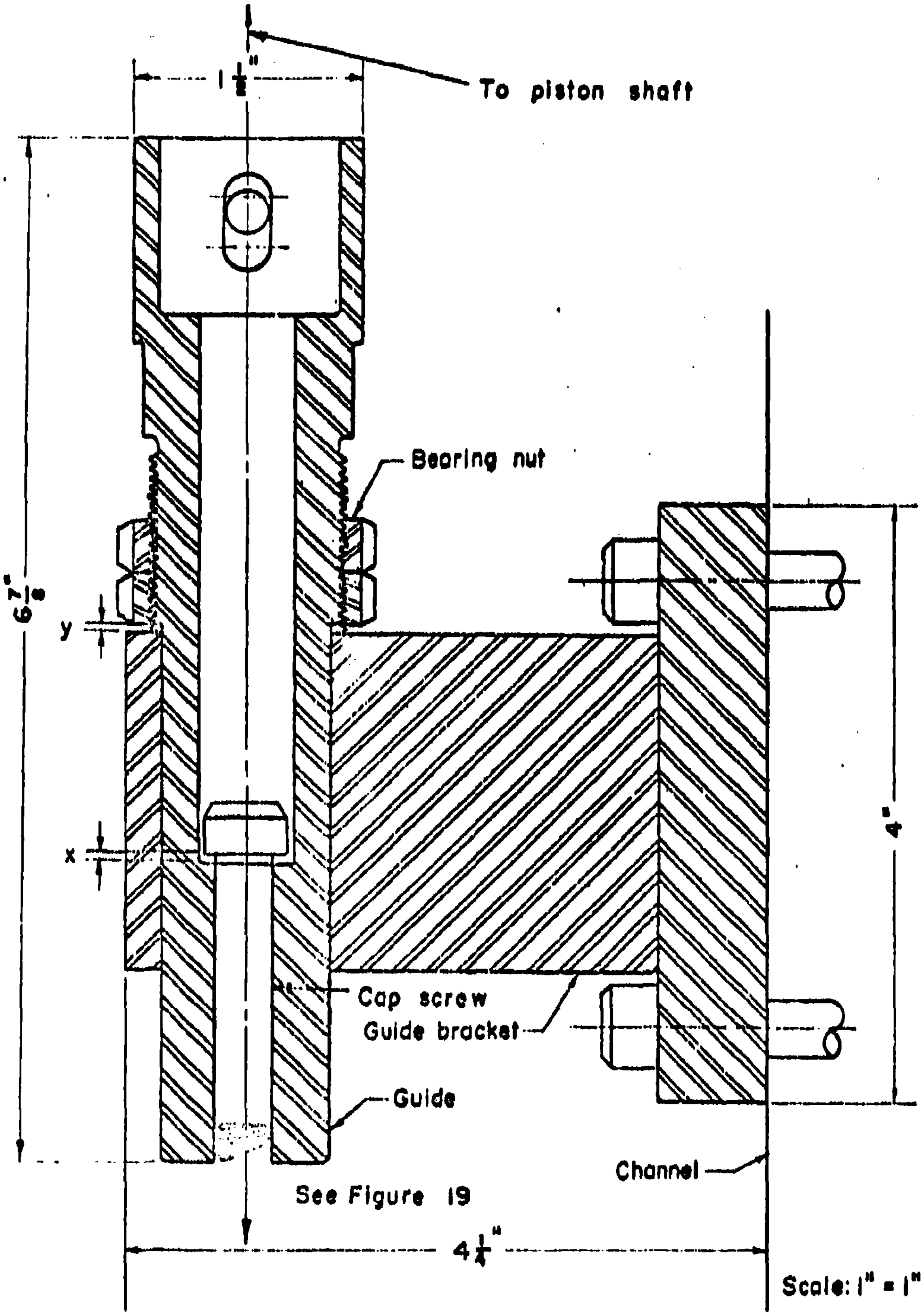


FIGURE 18. IMPROVED HOT-TENSION - TEST ASSEMBLY

A-5288

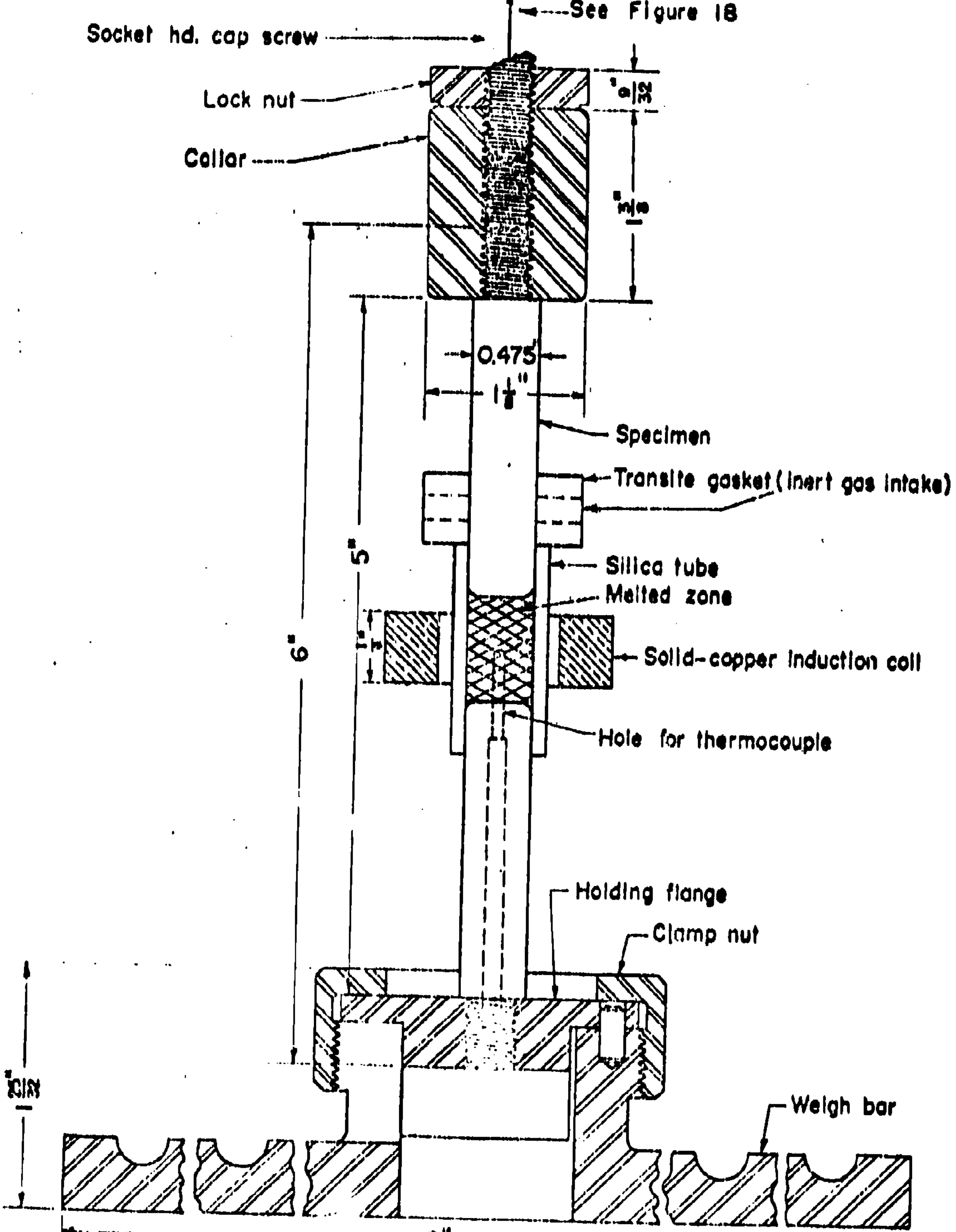


FIGURE 19. IMPROVED HOT-TENSION-TEST ASSEMBLY

A-5289

the specimen was melted, more metal was needed than was available to fill the oversize retaining sleeve. This, naturally, left voids as the melt cooled down, and this condition increased the normal problems expected from shrinkage.

Experience showed that the best results were obtained when the ID of the quartz sleeves was 0.008 inch greater than the diameter of the hot-tension specimens. Two methods were tried to size the ID of the as-received tubing to the desired value. In the first method, a 3/8-inch diamond wheel was used to grind undersize tubing. The grinding was slow and expensive. In the other method, oversize tubing was evacuated and then heated and drawn over a tungsten mandrel. This was comparatively easy and inexpensive and will be used in subsequent tests.

The second change is concerned with maintaining the alignment of the two halves of the specimen. The change is represented by the sleeve bearing (Figures 17 and 18) and the apparatus on the weigh bar (Figures 17 and 19).

The third change provides for free, unrestrained shrinkage during cooling to test temperature. The cap screw (Figure 18) is preset so that when the bearing nuts have moved the distance "y", the specimen can still shrink freely the distance "x". The cap screw also serves as a guide for alignment of the upper and lower halves of the specimen when the center is melted.

The fourth change in the apparatus helped to eliminate cavities. By setting the bearing nuts (Figures 17 and 18) according to the amount of oversize of the quartz sleeves, the guide (Figures 17 and 18) can be made to drop the distance "y" (Figure 18) by its own weight when the specimen melts. The specimen shortens an amount "y" as molten metal flows into the space between the specimen and the sleeve. This shortening action compensates for the loss of metal and prevents the formation of voids. It may be useful also to purge out gases from the melt.

In early tests, it was believed that some of the voids in the melted zones of tested hot-tension specimens may have been due to oxidation products. Therefore, an inert gas was introduced into the quartz tube (Figures 18 and 19). Argon was used in several experiments. Oxidation was not eliminated, indicating the need for more work on this part of the apparatus. However, it appears that shrinkage was more to blame than gases for void formation.

Temperature measurements were considered accurate within ±50 F on the basis of past experience and calibrations. In the hot-tension tests so far, temperature was measured at a point 1/8 inch from the edge of the melted zone, after calibrating with a thermocouple placed in the center of

the melted zone. Work has been started on measuring the temperature of the melt directly. Direct measurement should be more reliable than the indirect type. The disadvantage is possible contamination of the melt by the thermocouple material. To prevent contamination, high-purity alumina thermocouple protectors are being used.

A small number of tests were run with the modified equipment. An SAE 4340 specimen melted in one of these tests is shown in Figure 20, and to its left, for comparison, is shown another SAE 4340 specimen, which was melted using the original apparatus. The radiograph in Figure 21 shows the sound melted zone in the specimen referred to in Figure 20, right. Figure 22 shows the melted zone in a specimen melted before the apparatus was modified.

Tests with the modified apparatus had to be discontinued when the induction heating unit broke down midway through the report period. Replacement parts have been obtained and the necessary repairs made, and tests are being resumed.

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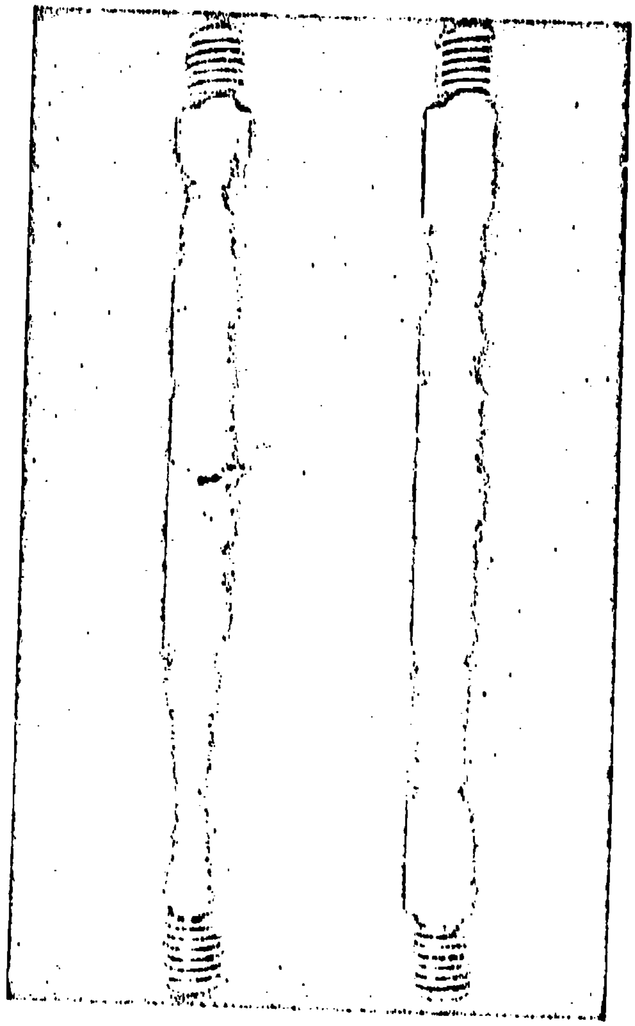

N875

FIGURE 20. SAE 4340 HOT-TENSION SPECIMENS MELTED BEFORE (LEFT) AND AFTER (RIGHT) APPARATUS WAS MODIFIED

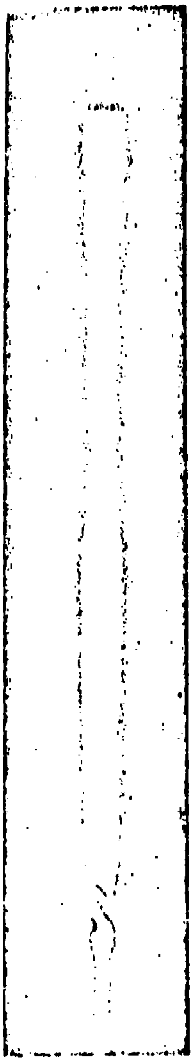

FIGURE 21. RADIOGRAPH OF SAE 4340 HOT-TENSION SPECIMEN MELTED AFTER APPARATUS WAS MODIFIED

7X Aqua Regia Etch 90294

FIGURE 22. PHOTOMACROGRAPH OF MELTED ZONE IN AN SAE 4340 STEEL SPECIMEN SHOWING CAST STRUCTURE AND SHRINKAGE CAVITY

APPENDIX II

APPENDIX II

Investigation of Weld-Metal Cracking Tests

Four types of weld-metal cracking tests had been tried as of August 12, 1952, the date of the last summary report, in an attempt to correlate cracking susceptibility with hot ductility. They were the double-vee butt joint, circular groove, circular patch, and double fillet. The double-vee butt-joint specimen was unsatisfactory, because it required restraint to make the weld deposit crack, and the restraint could not be reproduced accurately from test to test. The circular-groove and circular-patch tests seemed to be of the "go — no-go" variety on the basis of limited data. The double-fillet specimen was found to be too severe in its original form. It could be readily modified, however, so two series of tests were run in the present report period, using a less severe form. The results were inconclusive. Although they were encouraging, it was decided not to make additional tests immediately. Usually, there are many unknowns involved in a new test and several trial tests are required before the results are conclusive. Instead of going ahead with the double-fillet test, resort was made to a modification of the Lehigh restraint test, which was first reported in the literature in 1946[1].

The first modified specimen is shown in Figure 23. This differs from the original specimen in one respect: it consists of two parts, frame and insert, instead of being one solid plate. The idea was to conserve high-purity SAE 4340 steel by furnace brazing it in the form of an insert to a plain-carbon-steel frame. The restraint offered by the specimen to the weld is variable, increasing as "x" of Figure 23 is increased. For each weld-metal composition studied, a determination is made of the smallest "x" that will cause cracking. The more crack-sensitive weld-metal composition will be associated with the smaller "x" necessary for crack formation.

Two changes were made in the first modification. The first one substituted welding (E7015 electrode) for brazing, and the second one, a double-vee for a double-U joint (Figure 24). The advantages of welding over furnace brazing are: (1) it is a faster process; (2) it can better insure high hot strength; and (3) the weld joint can be designed to facilitate removal of the

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(1) Stout, R. D., Tör, S. S., McGeady, L. J., and Doan, G. E., "Quantitative Measurement of the Cracking Tendency in Welds". Welding Journal, 25 (9) 522s-531s (1946).

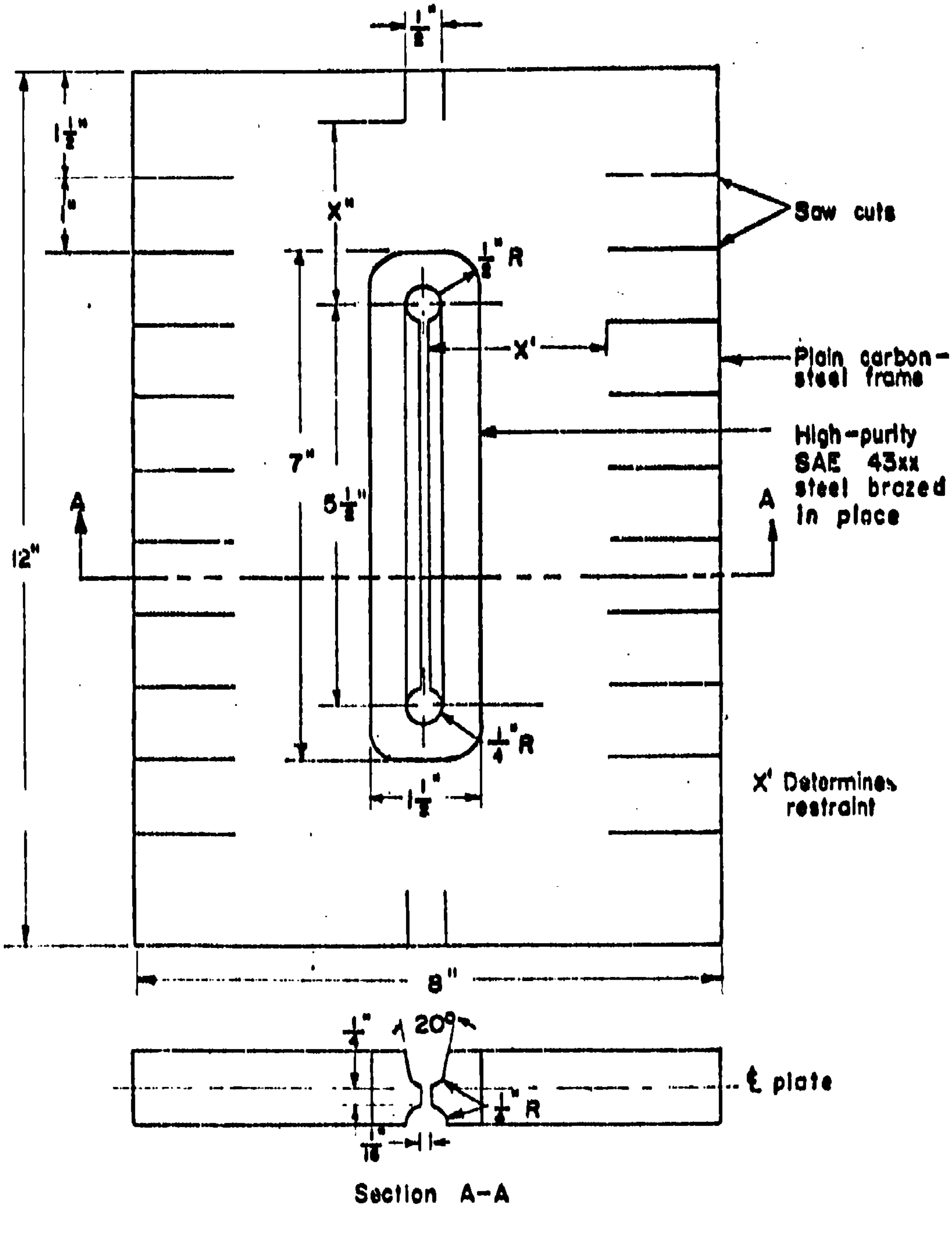

FIGURE 23. ORIGINAL MODIFICATION OF LEHIGH RESTRAINT SPECIMEN

A-5869

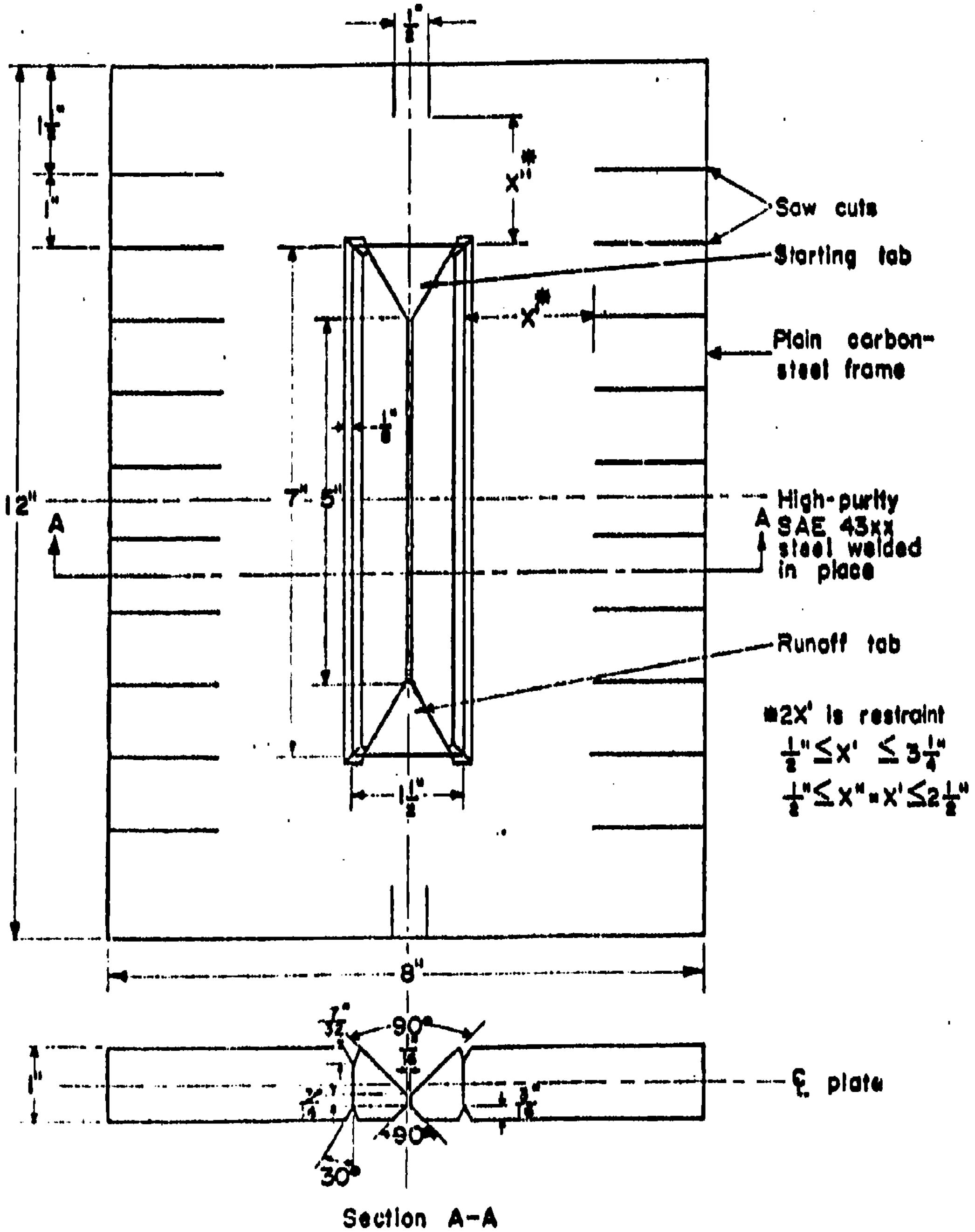

FIGURE 24. CURRENT MODIFICATION OF LEHIGH RESTRAINT SPECIMEN

A-7739

insert for inspection. Temperature measurements have indicated that the sides of the insert reach a maximum temperature of about 650 F during welding. Therefore, the air gap between the frame and the insert (Figure 24) should not affect the test results. With respect to the joint design, the double-vee-type joint is much less expensive to machine than the double-U type.

The steel compositions studied in cracking tests will be the same ones for which hot-strength and hot-ductility data are obtained. Filler wire of these compositions will be deposited in inserts of the same composition, using an inert-gas consumable-electrode process. This process was chosen because it is possible to deposit high-purity weld metals without contaminating them with elements from fluxes and other sources.

Tests were run to establish welding procedures and techniques and details in the specimen design. In these tests, commercial steel wire (3/32 inch) was deposited in plain-carbon-steel inserts. A set of conditions was established, which is presented below:

Wire feed - 90 ipm

Carriage speed - 15 ipm

Welding current - 370 to 390 amp

Arc voltage - 31 to 32 volts

Heat input - 47,880 joules per inch

Length of electrode consumed - 42 in.

Time of welding - 28 sec

"Time of welding" in the above list is total time, that is, the time required to weld a 7-inch length of joint. The length of joint under full restraint is only 5 inches, since starting and runoff tabs are used (Figure 24). The starting tab provides an opportunity to preadjust the arc length; the runoff tab reduces crater formation. A typical bead is 1/4 inch high, and is centrally located in the joint.

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